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6. AUTHOR(S) Leang S. Shieh				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Electrical Engineering University of Houston Houston, Texas 77204-4793			8. PERFORMING ORGANIZATION REPORT NUMBER	
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13. ABSTRACT (Maximum 200 words) A complete study of the principal n th root of a complex matrix and associated matrix-valued functions is presented in this research report. The principal n th root of a matrix is shown to be useful for the following: constructing the matrix-sign function and the (generalized) matrix-sector function; solving the matrix Lyapunov and Riccati equations; separating matrix eigenvalues relative to a circle, sector and a sector of a circle in the λ -plane; block-diagonalization (parallel decomposition) and block-triangularization (cascaded decomposition) of a general system matrix; generalizing the block-partial-fraction expansion of a rational matrix; and modelling a continuous-time system from the identified discrete-time model. Also, in this research report, new definitions and computational algorithms have been presented to determine the rectangular and polar representations of a complex matrix. Furthermore, their applications to control systems have been discussed. Finally, utilizing the developed algorithms, a multi-stage design procedure has been established to design discrete-time controllers to achieve pole-assignment in a specified region for a large-scale discrete-time multivariable system.				
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COMPUTATIONS, PROPERTIES AND APPLICATIONS OF MATRIX-VALUED FUNCTIONS TO MATHEMATICAL SCIENCE AND CONTROL SYSTEMS

Summary of Research Results

A complete study of the principal n th root of a complex matrix and associated matrix-valued functions is presented in this research report. This includes the development of techniques to compute the principal n th root of a matrix, study of associated matrix-valued functions, and their applications to mathematical sciences and control systems. First of all, a computationally fast and numerically more stable algorithm has been developed to compute the principal n th root of a complex matrix without explicitly utilizing its eigenvalues and/or eigenvectors. The principal n th root of a matrix is shown to be useful for the following: constructing the matrix-sign function and the (generalized) matrix-sector function; solving the matrix Lyapunov and Riccati equations; separating matrix eigenvalues relative to a circle, sector and a sector of a circle in the λ -plane; block-diagonalization (parallel decomposition) and block-triangularization (cascaded decomposition) of a general system matrix; generalizing the block-partial-fraction expansion of a rational matrix; and modelling a continuous-time system from the identified discrete-time model. Also, in this research report, new definitions and computational algorithms have been presented to determine the rectangular and polar representations of a complex matrix. Furthermore, their applications to control systems have been discussed. Finally, utilizing the developed algorithms, a multi-stage design procedure has been established to design discrete-time controllers to achieve pole-assignment in a specified region for a large-scale discrete-time multivariable system.

Based on the research results in the period of 1987-1990, twenty-seven papers have been published in the referred journals and listed as follows:

1. Shieh, L.S., H.M. Dib and S. Ganesan, "Linear Quadratic Regulators with Eigenvalue Placement in a Horizontal Strip," *International Journal of Systems Science*, Vol.18, No.7, pp.1279-1290, July 1987.

Abstract

A method for optimally shifting the imaginary parts of the open-loop poles of a multivariable control system to the desirable closed-loop locations is presented. The optimal solution with respect to a quadratic performance index is obtained by solving a linear matrix Lyapunov equation.

2. Shieh, L.S., J.S.H. Tsai and N.P. Coleman, "The Rectangular and Polar Representations of a Complex Matrix," *International Journal of Systems Science*, Vol.18, No.10, pp. 1825-1838, October 1987.

Abstract

This paper presents some new definitions of the real and imaginary parts and the associated amplitude and phase of a real or complex matrix. Computational methods,

which utilize the properties of the matrix sign function and the principal n th root of a complex matrix, are given for finding these quantities. A geometric series method is newly developed for finding the approximation of the matrix-valued function of $\tan^{-1}(X)$, which is the principal branch of the arc tangent of the matrix X . Several illustrative examples are presented.

3. Chang, F.R., L.S. Shieh and N.P. Coleman, "Synthesis of Voltage Matrix Fraction Descriptions with Cascade or Parallel Active RC Networks," *Proceedings of the IEE (England) Part G. Electronic Circuits and Systems*, Vol. 134, No.2, pp.95-102, April 1987.

Abstract

With the aid of the structural theories of multivariable control systems in the time domain and in the frequency domain, two simple methods are developed for the realisation of general voltage matrix fraction descriptions without using integrators and multiwinding transformers. The basic approach of the paper is to construct an auxiliary network, which contains sets of decoupled RC-voltage amplifier networks in a cascaded form or in a parallel form, for the establishment of accessible intermediate states and then apply state-feedback and state-feedforward control laws around the auxiliary network for the realisations of the desired overall voltage matrix fraction descriptions. The proposed methods provide simple procedures for the realisation of multivariable compensators and multiport filters for multivariable control systems and multiport networks.

4. Shieh, L.S., M.M.Mehio, and H.M. Dib, "Stability of the Second-order Matrix Polynomial," *IEEE Trans. Automatic Control*, Vol.AC-32, No.3, pp.231-233, March 1987.

Abstract

This note summarizes some existing stability and instability conditions of the second-order matrix polynomial which arises in the formulation of classical mechanics, aerodynamics, and robotic systems. Also, some sufficient conditions for stability or instability of the second-order matrix polynomial are newly developed via the relevant linear matrix equation obtained from the Lyapunov theory.

5. Chang, F.R., L.S. Shieh, and B.C.McInnis, "Inverse of Polynomial Matrices in the Irreducible Form," *IEEE Trans. Automatic Control*, Vol.AC-32, No.6, June 1987.

Abstract

An algorithm is developed for finding the inverse of polynomial matrices in the irreducible form. The computational method involves the use of the left (right) matrix

division method and the determination of linearly dependent vectors of the remainders. The obtained transfer function matrix has no nontrivial common factor between the elements of the numerator polynomial matrix and the denominator polynomial.

6. Shieh, L.S. , H.M.Dib, and S.Ganesan, "Continuous-time Quadratic Regulators and Pseudo-continuous-time Quadratic Regulators with Pole Placement in a Specific Region," *Proceedings of the IEE (England) Part D. Control Theory and Applications*, Vol. 134, No.5, pp.338-346, September 1987.

Abstract

A linear optimal quadratic regulator is developed, for optimally placing the closed-loop poles of multivariable continuous-time systems within the common region of an open sector, and the left-hand side of a line parallel to the imaginary axis in the complex s -plan, without explicitly utilising the eigenvalues of the open-loop systems. Also, a pseudo-continuous-time state-space method is developed, for finding the linear suboptimal quadratic regulator which suboptimally places the closed-loop poles of multivariable discrete-time systems within the common region of a circle, and the logarithmic spiral in the complex z -plan. An illustrative example is presented to demonstrate the effectiveness of the proposed procedures.

7. Shieh, L.S., S.R. Lian, and B.C. McInnis, "Fast and Stable Algorithms for Computing the Principal Square Root of a Complex Matrix," *IEEE Trans. Automatic Control*, Vol.AC-32, No.9,pp.820-822, Sept. 1987.

Abstract

This note presents recursive algorithms that are rapidly convergent and more stable for finding the principal square root of a complex matrix. Also, the developed algorithm are utilized to derive the fast and stable matrix sign algorithms which are useful in developing applications to control system problems.

8. Shieh, L.S., S.R. Lian, C.B. Park, and N.P. Coleman, "Fast and Stable Recursive Algorithms for Continuous-time and Discrete-time Model Conversions," *Computers and Mathematics with Applications*, Vol.14, No.8, pp.629-644, August 1987.

Abstract

Based on the Newton-Raphson method, this paper presents recursive algorithms that are rapidly convergent and more stable for modeling equivalent continuous-time (discrete-time) model from the available discrete-time (continuous-time) model for a fixed sampling period. The newly developed recursive algorithms relax the constraints imposed

upon the existing model conversion algorithms, and, thus, enhance the applications of microprocessors and associated microelectronics to digital control systems. A practical example is presented to demonstrate the effectiveness of the proposed procedures.

9. Shieh, L.S., S. Ganesan, and J.M. Navarro, "Transformations of a Class of Time-varying Multivariable Control Systems to Block Companion Forms," Computers and Mathematics with Applications, Vol.14, No.6, pp.471-477, June 1987.

Abstract

The problem of transforming a class of time-varying multivariable control system to the controllable and observable block companion forms is considered in this paper. The non-singular transformation matrices for obtaining the block companion forms are found in terms of the controllability and observability matrices and the conditions for the existence of such transformations is stated.

10. Wang, J.C., B.C. McInnis, and L.S. Shieh, "Control Strategies," Encyclopedia of Robotics, John Wiley and Sons, Inc. pp.265-275, 1988.

Abstract

The computed torque technique, the perturbation method method and the adaptive control method along with others such as variable structure control, optimal control, minimum-time and minimum-time-fuel control are discussed in this article.

11. Shieh, L.S., H.M. Dib, S. Ganesan, and R.E. Yates, "Optimal Pole Placement for State-feedback Systems Possessing Integrity," International Journal of Systems Science, Vol.19, No.8, pp.1419-1435, 1988.

Abstract

A sequential design procedure to design an optimal state-feedback system possessing integrity and good response is presented. A sufficient condition is derived for checking the integrity of the optimal closed-loop system. The matrix Lyapunov equation is used to obtain the optimal state-feedback control law that places the closed-loop poles in specified regions and to derive the sufficient condition for the integrity of the designed system against actuator failures. The effectiveness of the proposed method is demonstrated by illustrative examples.

12. Shieh, L.S., Y.L. Bao and N.P. Coleman, "Model Transformations for State-space Self-tuning Control of Multivariable Stochastic Systems," Stochastic Analysis and Appli-

Abstract

In the state-space self-tuning control of a class of multivariable stochastic systems, it is often required to transform the estimated state equations in an observer block companion form to the equivalent state equations in a controller block companion form and/or transform the estimated left MFD to the equivalent right MFD.

A long division method is developed in this article for finding the similarity transformation matrix, which transforms the estimated observable state to the controllable state, and for transforming the estimated left MFD to the right MFD, without utilizing the realized high-dimensional system matrices. The relationships between the realized system matrices in the state-space descriptions and the quotients and remainders of the long division of two polynomial matrices in the matrix fraction descriptions are developed. The proposed new procedure reduces the computational difficulties arising in the development of the state-space self-tuning controller; thus, it enables the state-space self-tuning to be more amenable to on-line adaptive control of multivariable stochastic systems.

13. Tsai, J.S.H., L.S. Shieh, and R.E. Yates, "Fast and Stable Algorithms for Computing the Principal n th Root of a Complex Matrix and the Matrix Sector Function," Computers and Mathematics with Applications, Vol.15, No.11, pp.903-913, 1988.

Abstract

This paper presents rapidly convergent and more stable recursive algorithms for finding the principal n th root of a complex matrix and the associated matrix sector function. The developed algorithms significantly improve the computational aspects of finding the principal n th root of a matrix and the matrix sector function. Thus, the developed algorithms will enhance the capabilities of the existing computational algorithms such as the principal n th root algorithm, the matrix sign algorithm and the matrix sector algorithm for developing applications to control system problems.

14. Shieh, L.S., H.M. Dib, and R.E. Yates, "Sequential Design of Linear Quadratic State Regulators Via the Optimal Root-locus Techniques," Proceedings of the IEE (England), Part D, Control Theory and Applications, Vol.135, No.4, pp.289-294, July 1988

Abstract

The paper considers the use of well known root-locus techniques for sequentially finding the weighting matrices and the linear quadratic state regulators of multivariable control systems in the frequency domain. The proposed sequential design method enables the retention of some stable open-loop poles and the associated eigenvectors in the closed-loop system, and it allows some optimal closed-loop poles to be placed in a specific

region of the complex plane, by sequentially assigning some virtual finite open-loop zeros (which are finite asymptotic poles of a virtual closed-loop system as the scalar gain factor goes to infinity). Moreover, it provides a design procedure for determining the weighting matrices and linear quadratic state regulators for optimal control of multivariable systems in the frequency domain. The selection for the state weighting matrix, via the proposed method, places emphasis on specific linear combinations of the states (of the designers choice), rather than prespecified linear combinations of the states (output) which often arise in practical applications. An illustrative example is provided to demonstrate the effectiveness of the proposed method.

15. Shieh, L.S., H.M. dib, and S.Ganesan, "Linear Quadratic Regulators with Eigenvalue Placement in a Specified Region," *Automatica*, Vol.24, No.6, pp.819-823, November 1988.

Abstract

A linear optimal quadratic regulator is developed for optimally placing the closed-loop poles of multivariable continuous-time systems within the common region of an open sector, bounded by lines inclined at $\pm \pi / 2k$ ($k= 2$ or 3) from the negative real axis with a sector angle $\leq \pi / 2$, and the left-hand side of a line parallel to the imaginary axis in the complex s -plane. Also, a shifted sector method is presented to optimally place the closed-loop poles of a system in any general sector having a sector angle between $\pi / 2$ and π . The optimal pole placement is achieved without explicitly utilizing the eigenvalues of the open-loop system. The design method is mainly based on the solution of a linear matrix Lyapunov equation and the resultant closed-loop system with its eigenvalues in the desired region is optimal with respect to a quadratic performance index.

16. Mehio, M.M., S. Ganesan, and L.S. Shieh, "Eigenstructure Assignment in Multivariable State-Feedback Design," *Control Theory and Adanced Technology*, (Japan), Vol.4, No.4 pp.483-488, December 1988.

Abstract

The simultaneous assignment of eigenvalues and eigenvectors in a linear multivariable system using a state-feedback controller is presented. The procedure is based on solving a set of linear equations providing an efficient and simple means to modify the system dynamic response. An illustrative example is presented to demonstrate the effectiveness of the proposed procedures.

17. Tsai, J.S.H., L.S. Shieh, and T.T.C.Shen, "Block Power Method for Computing Solvents and Spectral Factors of Matrix Polynomials," *Computers and Mathematics with Applications*, Vol.16, No.9, pp. 683-699. 1988.

Abstract

This paper is concerned with the extension of the power method, used for finding the largest eigenvalue and associated eigenvector of a matrix, to its block form for computing the largest block eigenvalue and associated block eigenvector of a non-symmetric matrix. Based on the developed block power method, several algorithms are developed for solving the complete set of solvents and spectral power factors of a matrix polynomial, without prior knowledge of the latent root of the matrix polynomial. Moreover, when any right/left solvent of a matrix polynomial is given, the proposed method can be used to determine the corresponding left/right solvent such that both right and left solvents have the same eigenspectra. The matrix polynomial of interest must have distinct block solvents and a corresponding non-singular polynomial matrix. The established algorithms can be applied in the analysis and/or design of systems described by high-degree vector differential equations and/or matrix fraction descriptions.

18. Shieh, L.S., Y.L.Bao, and F.R.Chang, "State-space Self-tuning Regulators for General Multivariable Stochastic Systems," *Proceedings of the IEE (England) Part D, Control Theory and Applications*, Vol.136, NO.1, pp.17-27, January 1989.

Abstract

The paper presents a state-space approach for the self-tuning control of general linear multivariable discrete-time stochastic systems with the number of inputs (controllability indices) equal to or different from the number of outputs (observability indices). The dynamic system is represented in the state-space innovation form with the Luenberger's canonical structure. The model parameters, as well as the Kalman gain, are identified via the least-squares ladder algorithm, without utilising the standard state-estimation algorithm. Also, to avoid the direct use of the Luenberger's canonical transformations, a long division method is introduced for quickly converting a reducible or irreducible left matrix fraction description (LMFD) to an irreducible right matrix fraction description (RMFD) and for constructing the Luenberger's transformation matrices. In conjunction with the state-space self-tuning control, an integral control is used so as to eliminate the steady-state errors and render the closed-loop system less sensitive to modelling errors. The proposed method will enhance the application of the state-space self-tuning concepts to a general class of multivariable stochastic systems.

19. Ganesan, S., L.S.Shieh, and R.E.Yates, "Sequential Design of Discrete Linear Quadratic Regulators via Optimal Root-locus Techniques," *AIJA Journal of Guidance, Control and Dynamics*, Vol.12, No.3, pp.435-438, May-June 1989.

Abstract

A sequential method that uses the classical root-locus techniques has been developed to determine the quadratic weighting matrices and the discrete linear quadratic regulators of multivariable control systems. In this proposed approach, at each recursive step, an intermediate unity rank state-weighting matrix containing some invariant eigenvectors of that open-loop system matrix is assigned. Also, at each step, an intermediate characteristic equation of the closed-loop system containing the invariant eigenvalues is created. In order to control the movement of the root-loci and choose desirable closed-loop poles, some virtual finite open-loop zeros are assigned to this characteristic equation. The designed optimal closed-loop system thus would retain some stable open-loop poles and have the remaining poles optimally placed at desired locations in the complex z plane.

20. Shieh, L.S., Y.J.Wang, and Y.L.Bao, "Canonical Model Transformations Via Long Division Method and Continued Fraction Methods," *International Journal of Systems Science*, Vol.20, No.6, pp.1019-1033, June 1989.

Abstract

A long division method based on a matrix euclidean algorithm and a continued fraction method based on a matrix Routh algorithm are developed. These are used for constructing a similarity transformation matrix which would transform an observer (controller) block companion to a controller (observer) block companion form, and for converting a reducible or an irreducible left (right) matrix fraction description to an irreducible right (left) matrix fraction description. The relationships between the state-space models and the corresponding rational matrices of a class of multivariable systems are also explored. The new procedures enable us to enhance the computational aspects of designing self-tuning controllers for on-line adaptive control of a class of multivariable systems.

21. Tsai, J.S.H., L.S.Shieh, J.L. Zhang, and N.P.Coleman, "Digital Redesign of Pseudo-continuous-time Suboptimal Regulators for Large-scale Discrete Systems," *Control Theory and Advanced Technology*, (Japan), Vol.5, No.1, pp.37-65, March 1989.

Abstract

A multi-stage pseudo-continuous-time state-space method is developed for designing large-scale discrete systems, which do not exhibit a two- or multi-time scale structure explicitly. The designed pseudo-continuous-time regulator places the eigenvalues of the closed-loop discrete system near the common region of a circle (concentric within the unit circle) and a logarithmic spiral in the complex z -plan, without explicitly utilizing the open-loop eigenvalues of the given system. The proposed method requires the solutions of small order Riccati equations only at each stage of the design. Based on matching all the states at all the sampling instants, a new digital redesign technique is presented

for finding the pseudo-continuous-time quadratic regulator. An illustrative example is presented to demonstrate the effectiveness of the proposed procedures.

22. Shieh, L.S., M.M.Mehio, and S. Ganesan, "Discrete Linear Quadratic Regulators with Eigenvalue Placement in Specified Regions," *International Journal of Systems Science*, Vol.20, No.9, pp.1713-1728, September 1989.

Abstract

A new procedure is presented for the design of discrete linear quadratic regulators in the frequency domain with eigenvalue placement at exact locations and/or within specified regions of the complex z-plane. The method utilizes the frequency domain optimality conditions for achieving the desired pole placement. Also, the proposed procedure is sequential and enables the retention of some stable open-loop eigenvalues and associated eigenvectors in the closed-loop system. An illustrative example is provided to demonstrate the effectiveness of the proposed method.

23. Shieh, L.S., X.M.Zhao, J. L. Zhang, "Locally Optimal-digital Redesign of Continuous-time Systems," *IEEE Trans. Industrial Electronics*, Vol.36, No.4, pp.511-515, November, 1989.

Abstract

This paper presents a new optimal digital redesign technique for finding a dynamic digital control law from the given continuous-time counterpart by minimizing a local quadratic performance index. The quadratic performance index is chosen as the integral of the weighted squared difference between the states of the original closed-loop system at any instant between each sampling period. The developed optimal digital redesign control law enables the states of the digitally controlled closed-loop system to closely match those of the original closed-loop system at any instant between each sampling period, and it can easily be implemented using microcomputer with a relatively large sampling period.

24. Shieh, L.S., Z.Liu, and N.P. Coleman, "Design of Linear Quadratic Regulators with Eigenvalue Placement in a Specified Region," *Control Theory and Advanced Technology*, (Japan), Vol.6, No.1, pp93-110, 1990.

Abstract

Two linear quadratic regulators are developed for placing the closed-loop poles of linear multivariable continuous-time systems within the common region of an open sector, bounded by lines inclined at $\pm \pi/2k$ (for a specified integer $k > 1$) from the negative real

axis, and the left-hand side of a line parallel to the imaginary axis in the complex s -plane, and simultaneously minimizing a quadratic performance index. The design procedure mainly involves the solution of either Lyapunov equations or Riccati equations. The general expression for finding the lower bound of a constant gain γ is also developed.

25. Shieh, L.S., J.L. Zhang, and S. Ganesan, "Pseudo-continuous-time Quadratic Regulators with Pole Placement in a Specific Region," *Proceedings of the IEEE (England) Part D, Control Theory and Applications*, 1990.

Abstract

The paper comments on the pseudo-continuous-time quadratic regulator developed in an earlier paper. It also presents a new digital redesign technique, based on matching all the states at all the sampling instants, for finding the pseudo-continuous-time quadratic regulator.

26. J.W. Sunkel and L.S. Shieh, "Optimal Momentum Management Controller for the Space Station," *AIAA Journal of Guidance, Control and Dynamics*, Vol.13, No.4, pp.659-688, July-August, 1990.

Abstract

This paper presents a new sequential design procedure for determining an optimal control moment gyro momentum management and attitude control system for Space Station Freedom. First, the space station equations of motion are linearized and uncoupled, and the associated state space equations are defined. Next, a new sequential procedure is used for the development of a linear quadratic regulator with eigenvalue placement in a specified region of the complex plane. The regional pole assignment method is used since it is best suited for tradeoffs between eigenvalue locations and robustness with respect to parameter variations, sensor failures, implementation accuracies, and gain reduction. The matrix sign function is used for solving the Riccati equations, which appear in the design procedure. Simulation results are given which show that the resultant design provides desired system performance.

27. Shieh, L.S., X.M. Zhao, N.P. Coleman, and J.W. Sunkel, "Two-stage Suboptimal Discrete-time Regulators for Continuous-time Stiff Dynamic Systems," *Applied Mathematical Modelling* Vol.14, pp.199-211, April 1990.

Abstract

A two-stage method is developed for design of linear quadratic regulators (LQRs) with regional pole assignment for a large-scale continuous-time stiff dynamic system and

its observer, which do not exhibit a two-time scale structure explicitly. The method also provides a procedure to convert the designed analog LQR and observer to an equivalent digital LQR and observer, respectively, for digital implementations. First, the large-scale stiff dynamic system is block-decomposed into two block-decoupled subsystems according to their own characteristics via the fast and stable matrix sign algorithm. Next, a sequential design procedure is used to design a LQR with regional pole placement for each subsystem. The same procedure is then carried out to design an optimal observer. For implementation of the designed analog LQR using a digital LQR, the designed analog LQR and observer are converted into an equivalent digital LQR and observer, respectively, via a digital redesigned method. A practical stiff system is used as an illustrative example to demonstrate the effectiveness of the proposed method.

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Scientific Personnel

H.M. Dib (Ph.D., 1987), D. Narayanan (M.S., 1987), Y.J. Wang (M.S., 1987), S. Ganesan (Ph.D., 1988), M.M. Mehio (Ph.D., 1988), J.S. Tsai (Ph.D., 1988), J.Q. Mao (M.S., 1988), H.H. Shen (M.S., 1988), J.L. Zhang (M.S., 1988), A.S. Tso (M.S., 1989), C.H. Chen (M.S., 1989), J.W. Sunkel (Ph.D., 1990).